Acta of Bioengineering and Biomechanics
Vol. 24, No. 2, 2022

Original paper
DOI: 10.37190/ABB-02021-2022-03

Can strength exercise affect the muscle oxygen saturation response?

CLAUDIA MIRANDA-FUENTES[1, 2], LUIS CHIROSA-RIOS[1], ISABEL GUISADO-REQUENA[3], FELIPE GARCÍA-PINILLOS[1, 5], INDYA DEL-CUERPO[1], ANTONIO LÓPEZ-FUENZALIDA[4], PAULINA IBACACHE-SAAVEDRA[2], DANIEL JEREZ-MAYORGA[1, 2]*

[1] Department of Physical Education and Sports, Faculty of Sport Sciences. University of Granada, Granada, Spain.
[2] Exercise and Rehabilitation Sciences Laboratory, School of Physical Therapy, Faculty of Rehabilitation Sciences, Universidad Andres Bello, Santiago, Chile.
[3] Department of Nursing, Physiotherapy and Occupational Therapy, Faculty of Nursing, Group of Preventive Activities in the University Health Sciences Setting, University of Castilla-La Mancha (Universidad de Castilla-La Mancha/UCLM), Albacete, Spain.
[4] Disciplinary Department of Kinesiology, Faculty of Health Science, Universidad de Playa Ancha, Valparaíso, Chile.
[5] Department of Physical education, Sports and Recreation, Universidad de La Frontera, Temuco, Chile.

Purpose: The objective of the study was to describe and compare the acute response of muscle oxygen saturation (SmO_2) and hemoglobin concentration (Hgb) in the vastus lateralis (VL) during resistance exercise protocols until failure. *Methods*: Sixteen males were considered (mean ± SD, age = 36.12 ± 6.40 years). Two familiarization sessions and one evaluation session were carried out where three force protocols were executed in the VL, one of them was isometric load (P1) and two of dynamic load (P2 and P3). SmO_2 [%] and Hgb [g/dL] were measured before and after each of these protocols. For P1, three series of 8 s of maximum isometric strength with the rest of 60 s between each set, the average isometric strength (AIS), and the isometric peak strength (IPS) were also recorded. After five minutes, P2 was performed, with an initial load of 40% of AIS. Then, at 30 minutes, P3 was performed considering an initial load of 40% of IPS. *Results*: The results suggest (I) minimum levels of SmO_2 (66.31 ± 9.38%) and Hgb (12.22 ± 0.55 g/dL) during P2, (II) no significant differences were observed between the average loads of the respective protocols for SmO_2 and (III) muscle Hgb differed significantly between rest with P1 and P3. *Conclusions*: Exercises of increasing intensity and of short duration do not significantly modify SmO_2. However, Hgb increases substantially compared baseline values.

Key words: *strength training, near-infrared spectroscopy, muscle oxygenation, oxygen consumption*

1. Introduction

Nowadays, new technologies such as near-infrared spectroscopy (NIRS) allow us to know in a specific way the metabolic behavior of muscle tissue associated with its oxygenation (muscle oximetry) in the face of different workloads [3]. Muscle oximetry is the study that enables us to estimate the partial pressure of muscle oxygen through the concentrations of oxygenated and deoxygenated hemoglobin, and can be measured using a NIRS [32]. These devices are non-invasive low-cost and functional instruments that make it possible for us to know the behavior of muscle oximetry and its derivatives in real-time through Bluetooth technology [28]. In addition, they have proven to be valid and reliable [7], [9], [10], [23], [28], [36]. Technically, NIRS illuminates skeletal muscle with light in the near-infrared spectrum and detects the light reflected through it. This type of light emitted at wavelengths in the infrared range (650–1000 nm) can enter biological tissues with less scattering and better

* Corresponding author: Daniel Jerez-Mayorga, PhD in Biomedicine, Fernandez Concha 700, Las Condes, Santiago, Chile. Phone: +56977697643, e-mail: daniel.jerez@unab.cl

Received: January 21st, 2022
Accepted for publication: April 6th, 2022

absorption than visible light [32], allowing NIRS to calculate changes in oxygenated hemoglobin (O_2Hb), deoxygenated hemoglobin (HHb), derived changes in total hemoglobin (tHb = O_2Hb + HHb) also expressed in percentage [%] as muscle oxygen saturation (SmO_2 = HbO_2 / tHb) [31], thus representing the behavior between supply and demand of oxygen in energy metabolism during muscular strength exercise [21].

When a muscle strength protocol is executed, an increase in oxygen consumption is caused depending on the intensity of the exercise, being reflected in the decrease in muscle oxygen saturation (SmO_2) [24], which leads to an increase in lactate levels in a blood as a response to accelerated glycolysis [9] showing the subject to feelings of fatigue and decreased physical performance [14], even influenced by age [2]. In this regard, Perrey et al. [32] established that a NIRS device can be used as a biomarker of skeletal muscle oxidative capacity and muscle performance, specifying that the higher the intensity of strength training, the higher the oxygen consumption in the musculoskeletal tissue. Other publications have examined SmO_2 during muscular strength exercise [5], [8], [12], [17], [30], reaching the same conclusions as the previous author. Along the same lines, an investigation that compared the SmO_2 response in the left vastus lateralis VL before and after the front and rear squats in the lower extremities established that the SmO_2 difference was not significantly different between these squat modalities [8]. Finally, a recent systematic review that aimed to report baseline and final SmO_2 reference values obtained with NIRS during strength training in healthy adults found that SmO_2 decreases as an acute response to muscular strength exercise in the VL, finding results before the strength protocol (range = 68.07–77.9%) and after (range = 9.50–77.9%) [27]. Regarding the NIRS sensor positioning protocol, in the review by Miranda-Fuentes et al. [27], all the articles selected according to the researchers' inclusion and exclusion criteria analyze the VL of the quadriceps. On the other hand, in the review proposed by Perrey et al., fifty-seven manuscripts were reviewed were thirty-seven of them evaluated SmO_2 in VL predominantly in aerobic sports and only two analyzed this variable during muscular strength training in the same muscle, which appears to be the preferred assessment site for the NIRS protocols, followed by the flexor digitorum profundus, flexor carpi, and gastrocnemius. The preference for evaluating VL could be explained by the different patterns of muscle use during cycling (as the sport most frequently evaluated with NIRS), where monoarticular muscles (VL) participate mainly in force generation, while biarticular muscles are responsible for force transmission, showing that the VL is more active than a biarticular one, such as the lateral gastrocnemius [27]. Currently, the parameters used for exercise prescription are usually systemic variables such as heart rate, maximum oxygen consumption, blood lactate, etc., that is, variables that are not very specific from a musculoskeletal point of view [38]. Despite the above, there is still little information that explains the behavior of SmO_2 and muscle strength exercises in healthy adults during dynamic and isometric strength exercises, so there are gaps in the application of the NIRS and their interpretation as a workload control method. Therefore, the objective of the study was to describe and compare the acute response of muscle oximetry (SmO_2) and hemoglobin concentration (Hgb) in the vastus lateralis during resistance exercise protocols until failure.

2. Materials and methods

2.1. Study design

A cross-sectional design study was carried out. It included two familiarization sessions one week before the start of the study to explain the procedures of each test and minimize possible execution errors; these sessions lasted 30 minutes each. One evaluation session of the variables was considered for which the volunteers were summoned with a 4-hour fast, without doing intense physical activity or consuming caffeine, tea, or any energizing drug or drinking alcohol 48 hours before exercise. This session began with the evaluation of body composition and anthropometry, to then give way to a moment of rest lying face up on a stretcher for 15 minutes; at this stage, SmO_2 (%), Hgb (g/dL), and vital signs at rest were evaluated. After this, the assessments of isometric muscle strength (P1), dynamic strength I (P2), and dynamic strength II (P3) were performed. The SmO_2 and Hgb were evaluated before, during and at the end of each strength protocol. The same investigator performed all evaluations under similar conditions and provided the same verbal cues to all participants. The evaluation session was carried out under environmental conditions of ~22 °C and ~60% humidity.

2.2. Subjects

Initially, twenty-three subjects were recruited for the study (five women and eighteen men) of which seven subjects (five women and two men) were excluded because it was not possible to read the SmO_2 and Hgb record on the device; coincidentally the subjects had the highest body fat percentage, which has been declared as a limitation for reading these devices [11]. Finally, sixteen healthy men volunteered to participate in this study (mean ± SD, age = 36.12 ± 6.40 years, body mass index (BMI) = 26.65 ± 2.73 kg/m^2, fat mass = 23.46 ± 4.85%, muscle mass 34.98 ± 3.70%, leg muscle mass 18.64 ± 2.17 kg). The inclusion criteria were being healthy adult subjects of both sexes, without altered acute health conditions, without medical comorbidities (chronic respiratory disease, subjects with a smoking habit), or a musculoskeletal condition that prevented them from performing physical activities. All subjects were informed of the procedures to be used and signed a written informed consent form before initiating their participation in the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the University of Granada Institutional Review Board (IRB approval: 997/CEIH/2019).

2.3. Procedures

Before starting the strength protocols, anthropometric variables were evaluated using a stadiometer for body height (Seca 202, Seca Ltd, Hamburg, Germany) and a bioimpedance assessment measure body composition (InBody 770, Cerritos, CA, USA).

2.3.1. Strength protocols

The strength protocols were evaluated using a functional electromechanical dynamometer FEMD (Dynasystem, Model Research, Granada, Spain), which is valid and reliable for muscle strength training [25], [28], [34], [35]. For this assessment, the participants sat on a chair specially designed for quadriceps evaluation. A pulley was fixed in the distal area of their dominant leg to provide the resistance assigned to each protocol (Fig. 1). In P1, each subject had to perform three sets of 8 seconds of maximum isometric strength with a rest of 60 seconds between each series, the instruction for this protocol was to perform a maximum effort knee extension. The maintenance of 8 seconds of isometric strength load has been considered due to the metabolic activation of the pathways that provide energy, with the oxidative pathway being the one that takes the most seconds to activate and be maintained over time. From P1, the average isometric strength load (AIS) and the peak isometric strength load (IPS) of each repetition were recorded. After a five-minute rest, the subjects performed P2, a protocol that began with an initial load of 40% of AIS, then after 30 minutes, P3 was performed, starting with a 40% of IPS load (Fig. 2). For the dynamic strength load exercises, each repetition increased 2 kg until reaching muscle failure, and the instructions were to perform knee extensions until reaching 180°.

Fig. 1. Evaluation of muscle strength P1, P2 and P3 and fixation of the dynamometer at the distal end of the leg to provide resistance to each protocol

2.3.2. Muscle oxygen saturation and hemoglobin concentration

For the muscular oximetry measurements, a NIRS (Humon Hex, Dynometrics Inc., Boston, New England) was used, being described as a valid and reliable instrument for the evaluation of muscle strength [9], [28] and high level of concordance with other Wireless NIRS devices available on the market [19]. Upon entering the laboratory and after anthropometric measurements, the participants had the NIRS installed at the midpoint of the thigh of the dominant leg between the anterior superior iliac spine and the upper edge of the patella, is secured with a velcro closure [3]. This variable was measured throughout the rest time, P1, P2, and P3 (Fig. 2).

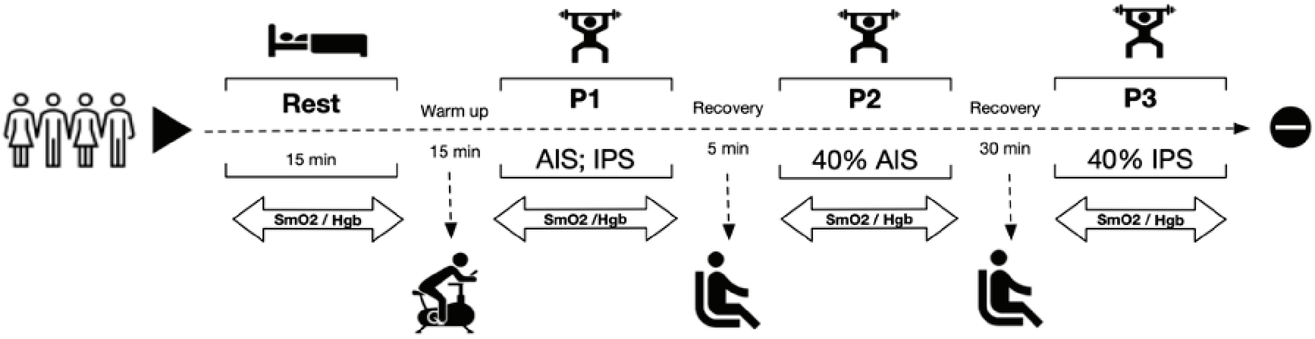

Fig. 2. Graphic representation of the three protocols and rest times for the measurement of muscle oxygen saturation and hemoglobin concentration. Rest – rest; P1 – isometric strength; AIS – average isometric strength; IPS – isometric peak strength; P2 – Dynamic strength with initial load 40% AIS; P3 – Dynamic strength with initial load 40% IPS; SmO_2 – muscle oxygen saturation; Hgb – hemoglobin concentration

2.3.3. Data extraction

The FEMD data [kg] were exported from the device to a personalized Excel® spreadsheet with the average and peak values of each series, considering the average of the three series for the analysis.

Moreover, to obtain the NIRS data, the device connects via Bluetooth to a smartphone and a personalized application (Dynamometrics Inc, Boston, New England, retrieved from http://humon.io) the data in real-time. The algorithms used to determine muscle oximetry hemodynamic parameters have not been published and are the property of Dynometrics Inc [9]. The total data recorded for each experimental session [% and g/dL] was also extracted into a spreadsheet (Excel®) on the NIRS website. For the precise extraction of these data from the web software, the start and end time of each protocol from rest to the last strength evaluation (seconds in the course of each time) was recorded in the data record form of each participant. For the analysis of the variables provided by the NIRS (SmO_2 and Hgb), the average value of the three sets was used for each protocol of isometric and dynamic strength both at the beginning and at the end of each one.

2.4. Statistical analyses

Descriptive data are presented as mean and standard deviation (SD). The normal distribution of the data (Shapiro–Wilk test) and the homogeneity of variances (Levene test) were confirmed ($p > 0.05$). For the main analysis, a repeated-measures analysis of variance (ANOVA) was conducted with Bonferroni post-hoc analysis. The Greenhouse-Geisser correction was used when the Mauchly sphericity test was violated. Omega squared (ω^2) was calculated for the ANOVA where the values of the effect sizes 0.01, 0.06 and above 0.14 were considered small, medium, and large, respectively [6]. Statistical significance was accepted at $p < 0.05$. The JASP statistics package (version 0.14.1) was used for statistical analyses.

Table 1. The behavior of the SmO_2, Hgb and strength during all protocols

Condition	Variable	Load [kg]	SmO_2 [%]	Hgb [g/dL]
Rest	–	–	66.72 ± 12.06	12.03 ± 0.37
P1	Average load	49.67 ± 9.13	69.45 ± 6.96	12.36 ± 0.56
	Maximum load	56.31 ± 9.90		
P2	Average load	27.00 ± 6.77	66.31 ± 9.38	12.22 ± 0.55
	Maximum load	47.39 ± 7.41		
	Number of repetitions	10.6 ± 2.3		
P3	Average load	29.15 ± 7.15	69.05 ± 9.95	12.36 ± 0.58
	Maximum load	50.00 ± 7.61		
	Number of repetitions	9.8 ± 2.5		

Data expressed as mean ± standard deviation. Rest – repose; P1 – isometric strength; P2 – Dynamic strength with initial load 40% AIS; P3 – Dynamic strength with initial load 40% IPS; SmO_2 – muscle oxygen saturation; Hgb – hemoglobin concentration [g/dL].

3. Results

The maximum load developed was during the P1 protocol (56.31 ± 9.90 kg). Maximum levels of SmO_2 (69.05 ± 9.95 %) and Hgb (12.36 ± 0.58 g/dL) were observed during P3 (Table 1).

There were no significant differences between average loads of the respective protocols for SmO_2: ($F_{1,25} = 2.246$, $P = 0.135$, $\omega^2 = 0.011$ (Fig. 3).

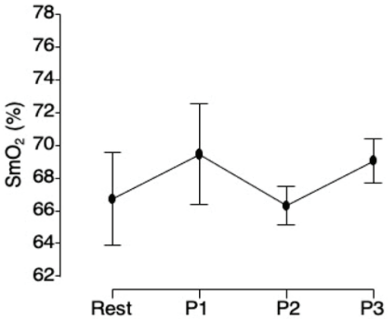

Fig. 3. Muscle oxygen saturation differences between rest and muscle strength protocols. Abbreviations: Rest – repose; P1 – isometric strength; P2 – Dynamic strength with initial load 40% AIS; P3 – Dynamic strength with initial load 40% IPS; SmO_2 – muscle oxygen saturation [%]

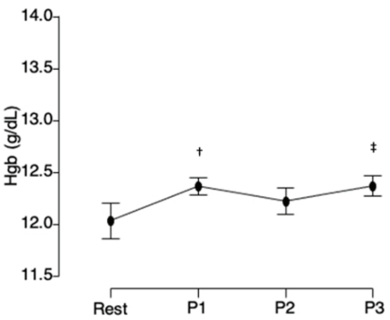

Fig. 4. Hemoglobin concentration differences between rest and muscle strength protocols. Abbreviations: Rest – repose; P1 – isometric strength; P2 – Dynamic strength with initial load 40% AIS; P3 – Dynamic strength with initial load 40% IPS; SmO_2 = muscle oxygen saturation; † – Significant differences between REST versus P1; ‡ – Significant differences between REST versus P3

The results in muscle Hgb differed significantly between rest and P1 and rest and P3 ($F_{2,30} = 7.353$, $p = 0.003$, $\omega^2 = 0.055$) (Fig. 4). The post-hoc analyses using Bonferroni correction revealed that hemoglobin concentration levels increased significantly between rest and P1 (mean difference = 0.334, $P = 0.011$) and between rest and P3 (mean difference = 0.336; $p = 0.023$) (Table 2).

4. Discussion

The aim of the study was to describe and compare the acute response of muscle oximetry (SmO_2) and hemoglobin concentration (Hgb) in the VL during resistance exercise protocols until failure. The main findings suggest that (I) minimum levels of SmO_2 (66.31 ± 9.38%) and Hgb (12.22 ± 0.55 g/dL) were observed during P2, (II) no significant differences between average loads of the respective protocols for SmO_2 were found and, (III) muscle Hgb differed significantly between rest and P1 and rest and P3. These findings could discriminate the dynamics of muscle O_2 saturation in the VL during different protocols and intensities in muscular strength exercises.

The results of this study indicate that the resting condition shows mean SmO_2 values of 66.72 ± 12.06%, which agrees with the baseline data from other studies [27]. Otherwise, neither P1, P2, and P3 seemed to significantly modify SmO_2 concerning rest, in a protocol of isometric strength of 3 seconds and another of isokinetic fatigue of knee extensors performing 15 repetitions at maximum intensity at a speed of 60° per second, they did not find significant differences in SmO_2 before and after the strength protocol between the experimental leg and the control leg [26].

Likewise, a recent study [13], where the oximetry of muscle tissue is considered with the tissue saturation index (TSI), which corresponds to one of four synonyms with which this variable can be found in the literature, also recognizing saturation muscle tissue oxygen (SmO_2), tissue oxygen saturation (StO_2) and

Table 2. Bonferroni post-hoc of hemoglobin concentration

Condition		Mean difference	Cohens'd	*p*-value
P1	P2	0.145	0.563	0.238
	P3	–0.002	–0.012	1.000
	Rest	0.334	0.948	0.011*
P2	P3	–0.147	–0.560	0.243
	Rest	0.189	0.423	0.667
P3	Rest	0.336	0.855	0.023*

Rest – repose; P1 – isometric strength; P2 – Dynamic strength with initial load 40% AIS; P3 – Dynamic strength with initial load 40% IPS; * $p < 0.05$.

tissue oxygenation index (TOI) [3], showed that this variable does not change after the application of 4 plyometric training protocols with different recovery periods between sets (1, 2, 3 and 5 minutes) ($p = 0.21$). In this study, it was observed that muscle saturation values returned to their baseline values regardless of the minutes of recovery. Despite the above, in P1 and P3, SmO_2 showed an increasing trend compared to baseline values, a situation that seems interesting to discuss given the discrepancy with respect to the results of this variable after a muscular strength exercise [27].

Some of the reasons that can justify this difference are that the workload used can influence on the response of the oximetry. Several studies considered submaximal loads and times under tension that was longer than the one proposed in this study, being the case of Gomez-Carmona [12] who used loads that varied between 60% 1RM (~20RM) and 75% 1RM (~10RM). In the same line, Davis [8] applied a protocol of 3 sets of 15 repetitions at 70% 1RM for front and rear squats, whereas Timon et al. used in their study 3 × 8 repetitions 75–80% 1RM and Alvares [1] performed series of 6 maximum voluntary contractions at fast speed (180° s^{-1}) during the knee extension phase, in comparison with the protocol of the present investigation which considered 8s for P1 and approximately 20–30 s for P2–P3, performing three sets with intra-repetition increases of 2 kg until muscle failure.

In this case, according to the intensity of the exercise applied, the increasing load of the exercise and the energy substrates demanded by it did not require a more significant presence of oxygen for its metabolism, and that is what the authors consider the main reason for the non-decrease in the SmO_2 [15]. In another way, the increase in muscle oxygenation can be explained from a physiological point of view where it is expected that the muscle tissue has an anticipatory and preparatory response in the initial seconds of the exercise, receiving an increase in its irrigation thanks to a redistribution of flows from inactive to active territories, which contributes to maintaining and improving oxygen reserves at the muscle level for energy processes that require a contribution of this element during exercise [16]. This response was also described in a previous study that analyzed the behavior of a subject during the execution of three muscle strength protocols [28].

Besides in P2, the behavior of SmO_2 tends to maintain or decrease slightly to rest. First, the questioning of these results indicates that the initial prescription of the workload influences the metabolic response of the tissue, proving to be more demanding a load from an average isometric value (P2) than a peak isometric value (P3). In this sense, an increase in the metabolic demand in the tissue was produced to generate more energy in a short time and prevent the physical limitations produced by the muscular fatigue imposed by the load [21]. It has been shown that the increase in work rates when performing muscular strength exercises increases the demands of oxygen in the skeletal muscle, which can exceed the capacity of the systems to supply it, especially in high-intensity exercises [33], where it has been established that the critical power is associated with the supply of oxygen in the tissues [20], and in exercises of muscular strength the increase of the intramuscular mechanical pressure can lead to a reduction of the blood flow [14]. This could result in transient muscular hypoxia [18], showing the subject to feelings of fatigue and decreased physical performance, which can be explained in this work by the tendency to decrease SmO_2.

In a study by Belardinelli [4], in which 11 subjects performed an incremental work exercise, it was shown that as the work rate intensified tissue oxygenation tended to decrease. On the other hand, a decrease in muscle oxygenation has also been associated to the point at which the work rate and the metabolic rate produce increases in the production of lactate in the blood due to an excess of carbon dioxide (CO_2), that is, where the additional extraction of oxygen is achieved mainly by reducing the hemoglobin saturation to a constant minimum oxygen partial pressure (PO_2) by the rightward shift of the oxyhemoglobin dissociation curve induced by the acidosis caused by the increased lactate [37].

Another of the results delivered in this study refers to muscular Hgb, where this variable differed significantly between P1 and P3 concerning the rest condition. In tissues, a PPO_2 of 26 mm Hg causes myoglobin to become more than 98% saturated; the great affinity that myoglobin shows for oxygen is essential for its biological function – capturing the oxygen supplied by blood hemoglobin for the cell [29]. In our study, the behavior of Hgb accompanies that of SmO_2. To date, there is little literature regarding the response of this variable during muscular strength exercise to contrast our results. However, these results are in line with those obtained by Lucero et al. [22] in the control group of their study during the progressive intensity 90-degree rhythmic isotonic knee extension exercise. Finally, trying to compare behaviors and determining if Hgb can discriminate the training load, in the present study, we found that exercising with maximum isometric strength and with dynamic strength starting with a load of 40% of pick isometric strength (P3) induced a significant increase in Hgb compared to rest and P2. In contrast, in this work, SmO_2 did not allow us to discriminate between protocols.

It is important to consider in the measurement of SmO_2 which parameters are considered in the different studies for their subsequent analysis and interpretation, in the study by Mead [26] for isometric strength, the mean oxygenation of the repetition that generated the greatest strength was used, and for the isokinetic fatigue protocol, the mean oxygenation of the first three repetitions and the last three repetitions was used. In the analysis by Davis [8], the maximum and minimum SmO_2 were determined before and after each series, and the difference was calculated as ΔSmO_2. In the study by Alvares [1], the SmO_2 baseline represents the average of 30 seconds before starting the exercise, it also incorporates the analysis of the amplitude of the muscle oxygen saturation that corresponds to the difference between the minimum value of SmO_2 reached during the exercise period and the baseline SmO_2. On the other hand, in the study by Gomez-Carmona [12] the loss of SmO_2 (∇% SmO_2) is considered, which corresponds to the relationship between SmO_2 at the beginning of the series and SmO_2 at the end of the series.

In conclusion, SmO_2 does not appear to change significantly with short-duration isometric exercises and intra-repetition variable resistance protocols from submaximal loads to muscle failure. However, Hgb varies substantially compared to the baseline values recorded in the study sample and maybe a potential indicator of internal muscle load, although studies are lacking to strengthen these findings.

This study was not without limitations. Our sampling was for convenience and to expand the small sample size. Unfortunately, this time it was only possible to evaluate men. However, the inclusion criteria of the study admitted both sexes, the admission of women was not possible due to aspects of body composition, the women admitted had BMI > 24.9 kg/m^2 and high% fat unlike men, coincidentally, the device could not register SmO_2 behavior in these cases. This limitation of wireless NIRS has been stated in the literature [11]. On the other hand, evaluating a single lower limb (dominant) with a recording of a single muscle (rectus femoris) is considered. Notwithstanding those limitations, the current study provides some insights into the acute response of muscle oximetry during strength training as well as is the first study to record acute changes in muscle strength in dynamic exercises using Humon Hex.

Future research could replicate this research idea by expanding the sample size, including both sexes, and exploring the behavior of this variable in other muscles to contrast and describe other metabolic behaviors in this regard.

5. Conclusions

The procedures analyzed in this study provide new knowledge regarding guidelines for the use of SmO_2 and Hgb as an internal load index. Monitoring muscle oximetry in physically active subjects through a NIRS device helps to specifically understand the behavior of skeletal muscle in real-time and the variation of SmO_2 and Hgb. Considering the results obtained in this study where isometric exercises and intra-repetition variable resistance until muscle failure do not present significant changes in the SmO_2 biomarker during their execution over time, it is assumed that the loads used did not metabolically request the muscle from an oxidative view despite applying muscle overload, so the proposed protocols can be used both in rehabilitation and by strength and conditioning trainers who wish to perform resistance training without requesting significant metabolic demands or experiencing symptoms of fatigue during the session. On the other hand, the Hgb biomarker evaluated with NIRS Humon Hex effectively shows significant changes after a resistance exercise, so it could initially be considered and used by trainers as an indicator of internal muscle load.

Acknowledgements

This paper is a part of Claudia Miranda-Fuentes Doctoral Thesis performed in the Biomedicine Doctorate Program of the University of Granada. This work was supported by DGI-University Andres Bello, No. DI-6-20/CBC.

References

[1] Alvares T.S., Oliveira G.V. de, Soares R., Murias J.M., *Near-infrared spectroscopy-derived total hemoglobin as an indicator of changes in muscle blood flow during exercise-induced hyperemia*, Journal of Sports Sciences, 2020, 38, 751–758.

[2] Bailey C.A., Yoon S.H., Côté J.N., *Relative variability in muscle activation amplitude, muscle oxygenation and muscle thickness: Changes with dynamic low-load elbow flexion fatigue and relationships in young and older females*, Journal of Electromyography and Kinesiology, 2021, 59.

[3] Barstow T.J., *Understanding near infrared spectroscopy and its application to skeletal muscle research*, Journal of Applied Physiology, 2019, 126, 1360–1376.

[4] BELARDINELLI R., BARSTOW T.J., PORSZASZ J., WASSERMAN K., *Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. / Modifications de l ' oxygenation du muscle squelettique lors d ' un exercice progressif, mesurees par spectroscopie infrarouge*, European Journal of Applied Physiology and Occupational Physiology, 1995, 70, 487–492.

[5] CALAINE INGLIS E., IANNETTA D., MURIAS J.M., *The plateau in the NIRS-derived [HHb] signal near the end of a ramp incremental test does not indicate the upper limit of O_2 extraction in the vastus lateralis*, American Journal of Physiology – Regulatory Integrative and Comparative Physiology, 2017, 313, R723–R729.

[6] COHEN J., *Statistical power analysis for the behavioral sciences*, 2nd ed., Hillsdale, Lawrence Earlbaum Associates, N.J., 1988.

[7] CRUM E.M., O'CONNOR W.J., VAN LOO L., VALCKX M., STANNARD S.R., *Validity and reliability of the Moxy oxygen monitor during incremental cycling exercise*, European Journal of Sport Science, 2017, 17, 1037–1043.

[8] DAVIS P.R., YAKEL J.P., ANDERSON D.J.F., *Muscle oxygen demands of the vastus lateralis in back and front squats*, International Journal of Exercise Science, 2020, 13, 734–743.

[9] FARZAM P., STARKWEATHER Z., FRANCESCHINI M.A., *Validation of a novel wearable, wireless technology to estimate oxygen levels and lactate threshold power in the exercising muscle*, Physiological Reports, 2018, 6, 1–14.

[10] FELDMANN A., SCHMITZ R., ERLACHER D., *Near-infrared spectroscopy-derived muscle oxygen saturation on a 0% to 100% scale: reliability and validity of the Moxy Monitor*, Journal of Biomedical Optics, 2019, 24, 1.

[11] FERRARI M., MOTTOLA L., QUARESIMA V., *Principles, Techniques, and Limitations of Near Infrared Spectroscopy*, 2004, 463–487.

[12] GÓMEZ-CARMONA C.D., BASTIDA-CASTILLO A., ROJAS-VALVERDE D., DE LA CRUZ SÁNCHEZ E., GARCÍA-RUBIO J., IBÁÑEZ S.J, et al., *Lower-limb Dynamics of Muscle Oxygen Saturation During the Back-squat Exercise: Effects of Training Load and Effort Level*, Journal of Strength and Conditioning Research, 2020, 34, 1227–1236.

[13] GUAN S., LIN N., YIN Y., LIU H., LIU L., QI L., *The effects of inter-set recovery time on explosive power, electromyography activity and tissue oxygenation during plyometric training*, Sensors, 2021, 21, 3015.

[14] HAMMER S.M., ALEXANDER A.M., DIDIER K.D., HUCKABY L.M., BARSTOW T.J., *Limb blood flow and muscle oxygenation responses during handgrip exercise above vs. below critical force*, Microvascular Research, 2020, 131, 104002.

[15] HARGREAVES M., SPRIET L.L., *Skeletal muscle energy metabolism during exercise*, Nature Metabolism 1–12, 2020.

[16] HEARON C.M., DINENNO F.A., *Regulation of skeletal muscle blood flow during exercise in ageing humans*, Journal of Physiology, 2016, 594, 2261–2273.

[17] HOPKER J.G., O'GRADY C., PAGEAUX B., *Prolonged constant load cycling exercise is associated with reduced gross efficiency and increased muscle oxygen uptake*, Scandinavian Journal of Medicine and Science in Sports, 2017, 27, 408–417.

[18] HUG F., LAPLAUD D., LUCIA A., GRELOT L., *EMG threshold determination in eight lower limb muscles during cycling exercise: A pilot study*, International Journal of Sports Medicine, 2006, 27, 456–462.

[19] JAÉN-CARRILLO D., ROCHE-SERUENDO L.E., CARTÓN-LLORENTE A., GARCÍA-PINILLOS F., *Agreement between muscle oxygen saturation from two commercially available systems in endurance running: Moxy Monitor versus Humon Hex*, Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 2021, 175433712110157.

[20] KELLAWAN J.M., BENTLEY R.F., BRAVO M.F., MOYNES J.S., TSCHAKOVSKY M.E., *Does oxygen delivery explain interindividual variation in forearm critical impulse?*, Physiological Reports, 2014, 2.

[21] KIRBY B.S., CLARK D.A., BRADLEY E.M., WILKINS B.W., *The Balance of Muscle Oxygen Supply and Demand Reveals Critical Metabolic Rate and Predicts Time to Exhaustion*, Journal of Applied Physiology, japplphysiol.00058.2021, 2021.

[22] LUCERO A.A., ADDAE G., LAWRENCE W., NEWAY B., CREDEUR D.P., FAULKNER J. et al., *Reliability of muscle blood flow and oxygen consumption response from exercise using near-infrared spectroscopy*, Experimental Physiology, 2018, 103, 90–100.

[23] MANCINI D.M., BOLINGER L., LI H., KENDRICK K., CHANCE B., WILSON J.R., *Validation of near-infrared spectroscopy in humans*, Journal of Applied Physiology, 1994, 77, 2740–2747.

[24] MANIMMANAKORN N., ROSS J.J., MANIMMANAKORN A., LUCAS S.J., HAMLIN M.J., *Effect of whole-body vibration therapy on performance recovery*, International journal of Sports Physiology and Performance, 2015, 10, 388–395.

[25] MARTINEZ-GARCIA D., RODRIGUEZ-PEREA A., BARBOZA P., ULLOA-DÍAZ D., JEREZ-MAYORGA D., CHIROSA I. et al., *Reliability of a standing isokinetic shoulder rotators strength test using a functional electromechanical dynamometer: effects of velocity*, PeerJ, 2020, 8, e9951.

[26] MEAD A.C., MCGLYNN M.L., SLIVKA D.R., *Acute effects of functional dry needling on skeletal muscle function*, Journal of Bodywork and Movement Therapies, 2021, 26, 123–127.

[27] MIRANDA-FUENTES C., CHIROSA-RÍOS L.J., GUISADO-REQUENA I.M., DELGADO-FLOODY P., JEREZ-MAYORGA D., *Changes in muscle oxygen saturation measured using wireless near-infrared spectroscopy in resistance training: A systematic review*, International Journal of Environmental Research and Public Health, 2021, 18.

[28] MIRANDA-FUENTES C., GUISADO-REQUENA I.M., DELGADO-FLOODY P., ARIAS-POBLETE L., PÉREZ-CASTILLA A., JEREZ-MAYORGA D. et al., *Reliability of low-cost near-infrared spectroscopy in the determination of muscular oxygen saturation and hemoglobin concentration during rest, isometric and dynamic strength activity*, International Journal of Environmental Research and Public Health, 2020, 17, 1–14.

[29] MYERS C., *Muscle Oxygenation Applications to Endurance Training*, Iris Publishers, 2020.

[30] PARADIS-DESCHÊNES P., JOANISSE D.R., BILLAUT F., *Sex-specific impact of ischemic preconditioning on tissue oxygenation and maximal concentric force*, Frontiers in Physiology, 2017, 7.

[31] PEIKON E., *The Future is NIRS: Muscle Oxygen Saturation as an Estimation of The Power-Duration Relationship*, Anat. and Physiol. Open Access J., 2020, 1.

[32] PERREY S., FERRARI M., *Muscle Oximetry in Sports Science: A Systematic Review*, Sports Medicine (Auckland, NZ), 2018, 48, 597–616.

[33] POOLE D.C., RICHARDSON R.S., *Determinants of oxygen uptake: Implications for exercise testing*, Sports Medicine, 1997, 24, 308–320.

[34] RODRIGUEZ-PEREA Á., JEREZ-MAYORGA D., GARCÍA-RAMOS A., MARTÍNEZ-GARCÍA D., CHIROSA RÍOS L.J., *Reliability and con-*

current validity of a functional electromechanical dynamometer device for the assessment of movement velocity, Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 175433712098488, 2021.

[35] RODRIGUEZ-PEREA A., RÍOS L.J.C., MARTINEZ-GARCIA D., ULLOA-DÍAZ D., ROJAS F.G., JEREZ-MAYORGA D. et al., *Reliability of isometric and isokinetic trunk flexor strength using a functional electromechanical dynamometer*, PeerJ, 2019.

[36] STONE K.J., FRYER S.M., RYAN T., STONER L., *The validity and reliability of continuous-wave near-infrared spectroscopy for the assessment of leg blood volume during an orthostatic challenge*, Atherosclerosis, 2016, 251, 234–239.

[37] STRINGER W., WASSERMAN K., CASABURI R., PORSZASZ J., MAEHARA K., FRENCH W., *Lactic acidosis as a facilitator of oxyhemoglobin dissociation during exercise*, Journal of Applied Physiology, 1994, 76, 1462–1467.

[38] THORNTON H.R., DASCOMBE B., *Developing Athlete Monitoring Systems in Team Sports: Data Analysis and Visualization*, International Journal of Sports Physiology and Performance, 2019.